Automatic Sensor-Fault Detection System for Comprehensive Structural Health Monitoring System

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ABSTRACT

Structural health monitoring systems are viewed as viable means to reduce life-cycle costs, increase structural reliability and extend the operational hours for a wide variety of composite structures found in numerous air platforms ranging from rotorcraft to unmanned air vehicles. The system enables the constant monitoring of structural integrity and hence provides users with an assessment tool for determining the location and extent of damage, which will eventually develop and grow over time as a result of improper use or normal day-to-day operation. Errors as a result of sensor damage and/or failure could lead to erroneous readings by a built-in diagnostic system such as the Acellent's SMART System, which makes use of a network of piezoelectric elements to detect damage in the structure. One of the major challenges of having a reliable structural monitoring system is to distinguish false alarms by sensors that had sustained damage during service from actual working sensors. Typical sensor damage includes sensor breakage, crushing of the sensors and sensor debond from host structure. This paper will discuss preliminary work that had been undertaken to increase the reliability of the SMART System by incorporating a simple circuitry for the purpose of automatic sensor fault isolation.

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Structural health monitoring systems are viewed as viable means to reduce life-cycle costs, increase structural reliability and extend the operational hours for a wide variety of composite structures found in numerous air platforms ranging from rotorcraft to unmanned air vehicles. The system enables the constant monitoring of structural integrity and hence provides users with an assessment tool for determining the location and extent of damage, which will eventually develop and grow over time as a result of improper use or normal day-to-day operation. Errors as a result of sensor damage and/or failure could lead to erroneous readings by a built-in diagnostic system such as the Acellent's SMART System, which makes use of a network of piezoelectric elements to detect damage in the structure. One of the major challenges of having a reliable structural monitoring system is to distinguish false alarms by sensors that had sustained damage during service from actual working sensors. Typical sensor damage includes sensor breakage, crushing of the sensors and sensor debond from host structure. This paper will discuss preliminary work that had been undertaken to increase the reliability of the SMART System by incorporating a simple circuitry for the purpose of automatic sensor fault isolation.

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INTRODUCTION

Numerous works had also been done in the past by researchers [1-4] in using impedance-based techniques to detect structural damage and sensor disbond. These measurements are typically performed using an impedance analyzer, which costs as much as $46,000 (such as Agilent E4991A RF Impedance/Material Analyzer). Besides being costly, typical impedance measurement devices are also rather bulky. In order to make this technique usable in the field, there is a need to reduce the size and cost of this equipment.

The active sensing technique employed by Acellent's SMART System utilizes a collective group of sensors provided by Acellent's SMART Layer, which are spatially distributed over the structure, to transmit and detect stress waves traveling through the structure. The piezoceramic disks encapsulated within the SMART Layer interact with the SMART Suitcase and a diagnostic software tools to provide an assessment of the structural integrity. This system has been successfully demonstrated in various applications both in the laboratory and in the field [5-8]. The accuracy and reliability of this built-in structural health monitoring system relies heavily on the accuracy of the measurements made by the sensors and the supporting wiring network.

Any failure of the sensors or the wiring components could cause the either false positives or false negatives. There is thus a need for a sensor diagnostic tool that will enable the realization of a comprehensive and intelligent structural health monitoring system. This can be done by employing a basic LCR (Inductor-Capacitor-Resistor) circuitry to measure changes to the piezoceramic sensor. By treating the piezoceramic sensor as a capacitor, one can design a simple voltage-divider circuitry to measure the voltage across the capacitor and use the measurements to infer the capacitance (or the impedance) of the piezoceramic sensor. While the intrinsic property of a capacitor is constant for a wide range of frequency, the capacitance of the piezoceramic sensor changes is known to change with frequency.

This paper documents the results of a feasibility study on sensor self-diagnostics using existing SMART Suitcase electronics as part of an overall effort [9] to enhance the capabilities of the active sensing system. The SMART Suitcase is a portable diagnostic hardware that is part of a structural health monitoring system developed by Acellent Technologies, Inc. Currently, sensor failure and disbond detection relies on a combination of visual inspection and the experience of the end user of active sensing system. There is a need to include a set of self-diagnostic sensing system within the SMART Suitcase to detect the integrity of the sensors themselves prior to using the active sensing system. This would reduce, if not remove, any the errors due to faulty sensors, and thereby enhancing the reliability of the structural health monitoring system.

OBJECTIVES

Using existing electronics of the SMART Suitcase and additional circuit components, the objectives of this test plan are as follows:

a) Construct a simple voltage-divider circuit to measure impedance changes for a single piezoceramic sensor
b) Identify the effect of sensor debond and impact-induced damage on impedance measurement using the proposed circuitry

TEST SETUP

A simple circuitry was set up to enable sensor self-diagnostics of the piezoceramic sensors. The piezoceramic sensor used was a circular disk with a diameter of 0.25 inch and a thickness of 0.01 inch. The material is made out of lead-zirconate-titanate (PZT) and it has a Curie temperature of 360 F.

The piezoceramic sensor is modeled as a capacitor of unknown capacitance in this setup. This is shown in Figure 1. The input voltage source is a sinusoidal input of known amplitude, V_i, which is provided by a function generator inside the SMART Suitcase. The resistor selected was 2KΩ. The output voltage, V_o, across the piezoceramic sensor was measured using Gage CS1250 data acquisition board inside the SMART Suitcase. The measurements of the output voltage V_o were made for frequencies ranging from 5 KHz through 1MHZ, with the frequency sweep done manually.

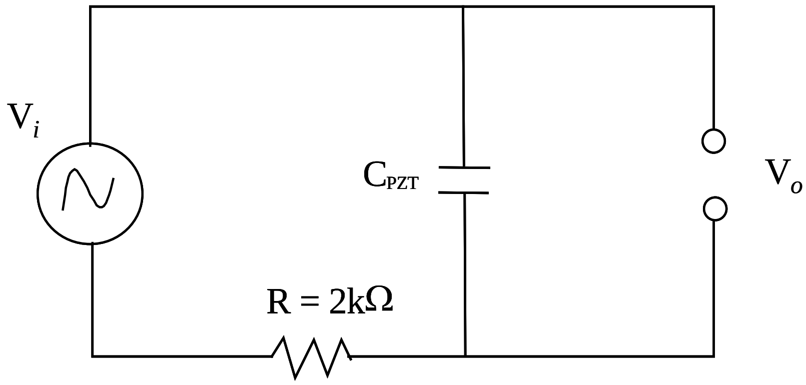
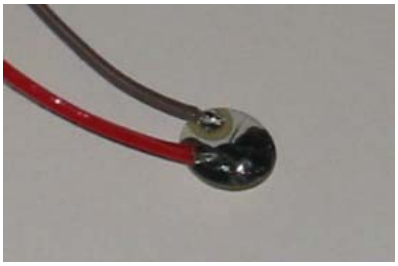


Figure 1: Schematic diagram of test circuit

The pictures shown in Figure 2 show the test specimens used. This circuitry will be used to test various conditions of a single piezoceramic sensor given as follows:

1) Unbonded, freestanding piezoceramic
2) Piezoceramic sensor encapsulated in SMART Layer, bonded to a carbon composite structure
3) Piezoceramic sensor encapsulated in SMART Layer, impacted by hammer 3 times
4) Piezoceramic sensor encapsulated in SMART Layer, impacted by hammer 6 times
5) Piezoceramic sensor encapsulated in SMART Layer, impacted by hammer 9 times
6) Piezoceramic sensor encapsulated in SMART Layer, impacted by hammer 15 times

The purpose of testing Condition (1) and Condition (2) is to determine if complete disbond can be differentiated from the measurements made. To simulate sensor integrity, the piezoceramic sensor is repeatedly impacted, (Conditions 3 through 6) with a hammer and the measurements are made after every fixed number of impacts. The piezoceramic sensor was totally destroyed after 15 impacts by the hammer.


(a) Freestanding piezoceramic sensor


(b) Piezoceramic sensor in SMART Layer


(c) Piezoceramic sensor encapsulated in SMART Layer and mounted on CFRP test structure

Figure 2: Pictures showing different conditions of the piezoceramic sensor

Figure 3:Hammer (2 lbm) used for impacting on sensor to induce sensor damage

RESULTS AND DISCUSSION

A simple resistor-capacitor (RC) model can be constructed by modeling the piezoceramic sensor as a capacitor. However, unlike the capacitor, the capacitance of the piezoceramic element changes with frequency. The impedance of the piezoceramic sensor, if modeled as a capacitor, is purely imaginary and is given by:

$$Z_{PZT} = \frac{1}{j2\pi f C_{PZT}} \qquad \text{...(1)}$$

where *f stands for frequency measured in units of Hertz (Hz)*
and *C_{PZT} the piezoceramic capacitance measured in Farads (F)*

The voltage ratio, V_0/V_i, which is the output voltage measured across the piezoceramic sensor normalized by the input voltage, is given by:

$$\frac{V_o}{V_i} = \frac{Z_{PZT}}{Z_{PZT} + R} \qquad \text{…(2)}$$

By combining these 2 equations, Equation (2) can be further reduced to

$$\frac{V_o}{V_i} = \frac{1}{1 + j2\pi f R C_{PZT}} \qquad \text{…(3)}$$

Using Equation (3), the capacitance of the piezoceramic sensor can be calculated using the following formula:

$$C_{PZT} = \frac{\sqrt{1 - (\frac{V_0}{V_i})^2}}{2\pi f R \frac{V_0}{V_i}} \qquad \text{…(4)}$$

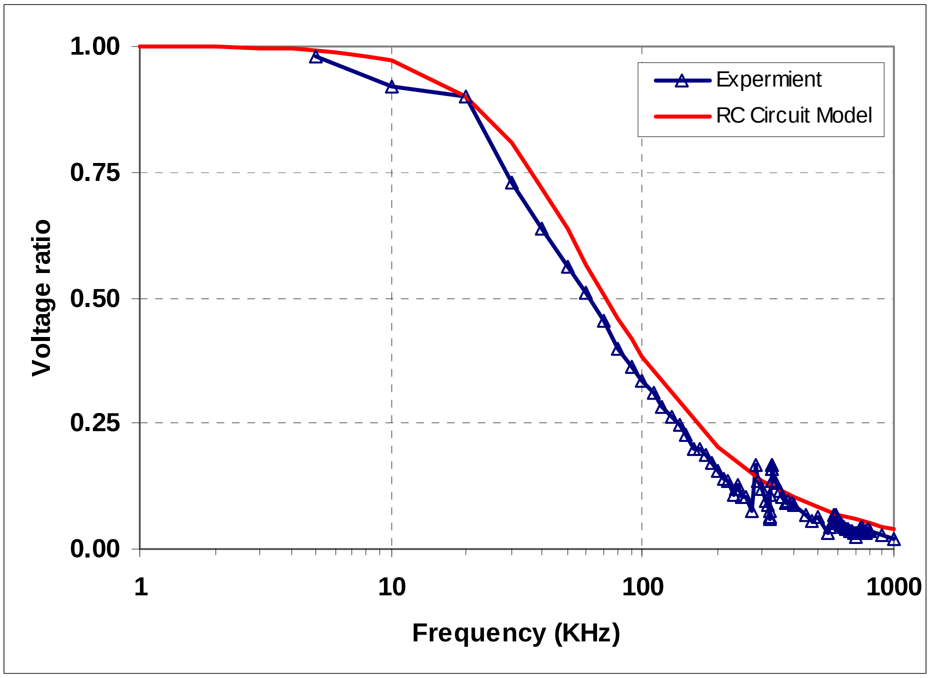


Figure 4: Comparing measurements of freestanding piezoceramic and calculations using RC circuit model

Figure 4 shows a comparison of the results obtained for a freestanding piezoceramic sensor and that calculated using Equation (3) for a C_{PZT} value of 1.93 nF. The capacitance of the piezoceramic is based on the relative permittivity value of 1750 (provided by APC international for APC 850 material) and circular disk with quarter inch diameter and one-tenth of an inch in thickness. This shows that the RC circuit model is a reasonable model to use for obtaining the capacitance of the piezoceramic sensor under various conditions.

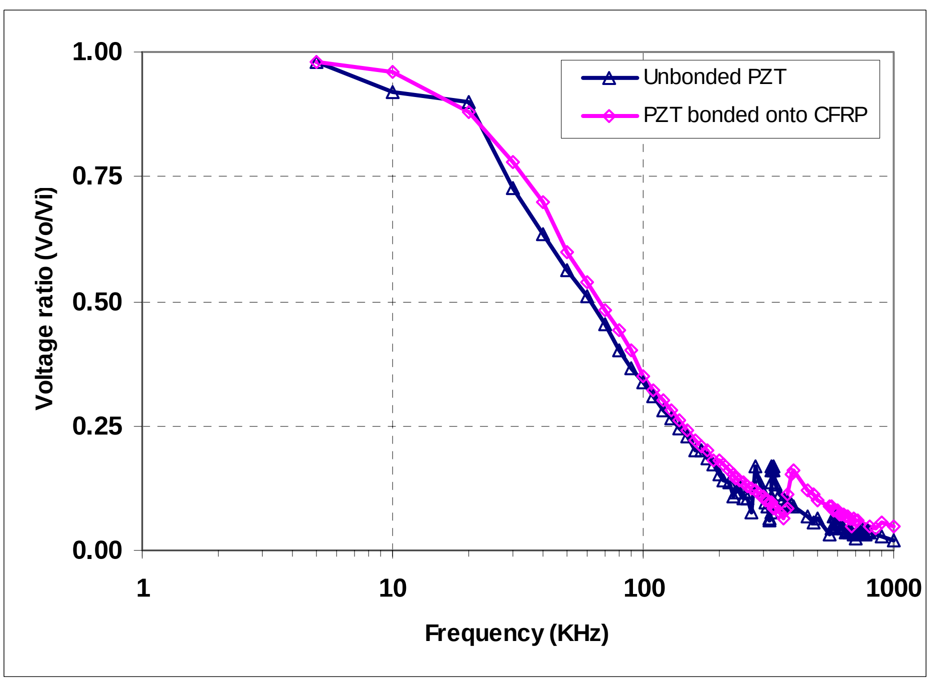


Figure 5: Effect of bonding PZT onto CFRP structure

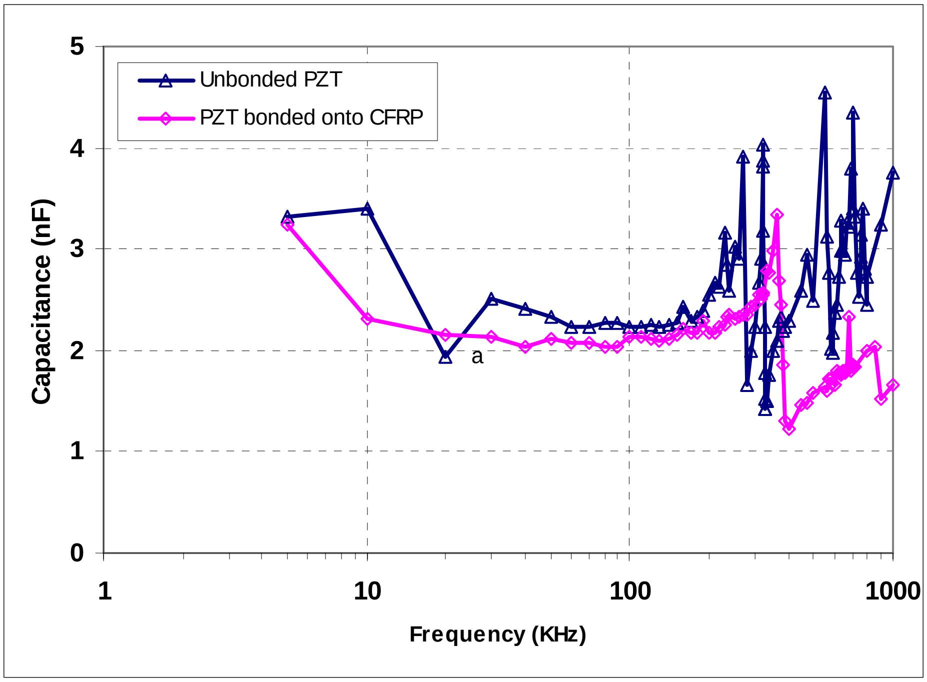


Figure 6: Change in capacitance as a result of bonding to CFRP structure

Figure 5 shows the voltage measurements for the piezoceramic sensor alone and when it is bonded onto a structure. When the piezoceramic sensor is free and not attached to any structure, the general behavior is to be expected. The 2 spikes at a frequency of 300 KHz and 360KHz correspond to the resonance frequencies of the piezoceramic sensor. When the piezoceramic sensor is bonded to the structure, the voltage ratio V_0/V_i, contains one single spike, which is very likely due to the change in boundary conditions of the piezoceramic sensor from the CFRP structure.

Figure 6 shows the capacitance values calculated using Equation (4) for the conditions corresponding to the voltage measurements shown in Figure 5. The multiple spikes that occur between 250KHz through 1 MHz for the freestanding piezoceramic sensor are attributed to the existence of multiple resonance modes. Compared to the plot shown in Figure 5, the sensitivity of the capacitance to frequency is more obvious in Figure 6. This is due to the coupled effect of the frequency as indicated by Equation (3). When the sensor is bonded onto the structure, the capacitance is significantly altered. In general, the capacitance is reduced and there are fewer spikes as compared to the freestanding piezoceramic sensor.

Sensor damage was simulated by taking a hammer shown in Figure 3 and directly striking the sensor with the rounded end of the hammer. The head of the hammer, weighing 2 lbm (5kg), was lifted up to a height of 12 inches and gravity was allowed to take over to guide the head onto the top of the sensor to be tested. Measurements were taken after every 3 hammer impacts, up until a total of 15 hammer impacts. Figure 7 compares the capacitance values calculated for the 6 different conditions of the piezoceramic sensor.

In general, the capacitance of the piezoceramic sensor is reduced as its structural integrity is degraded through repeated hammer impacts. The damage sustained by the sensor as a result of the impact could be a combination of internal cracking and pulverization of the dielectric medium thus reducing its ability to store charges. It is purported that the damage induced by the hammer strikes degrades the dielectric properties of the piezoceramic and /or reduces the area available to store charges. As such, the general trend in capacitance reduction is within expectation.

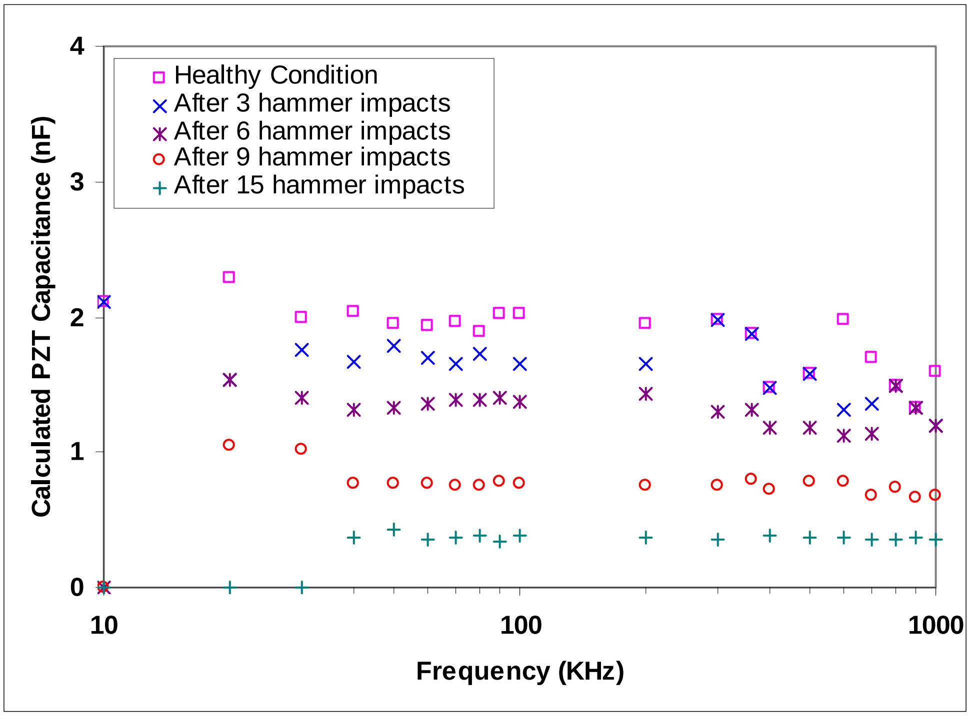


Figure 7: Effect of sensor degradation by impact on PZT capacitance

CONCLUSIONS

In conclusion, the combined use of a simple voltage-divider circuitry with existing electronics of the SMART Suitcase and the assumption of the sensor as a capacitor show promise of being able to determine both the bond condition and structural integrity of the sensor.

In particular, the results of this study show the following:

1. Bonding of sensor to a structure reduces the capacitance and cause significant changes to the resonance frequencies
2. Sensor degradation reduces the capacitance of the sensor over a wide range of frequencies

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